EXPERIMENTAL MEASUREMENTS OF THE MUELLER SCATTERING MATRIX FOR MARINE MICRO-ORGANISMS

Patricia G. Hull
Tennessee State University
Department of Physics and Mathematics
3500 John Merritt Blvd.
Nashville, TN 37209-1561
Phone/FAX: 615-963-5846   e-mail address: phull@harpo.tnstate.edu
Award No: N00014-96-1-0307

LONG-TERM GOAL

The long term goals of this project are to understand and quantify light scattering from ensembles of both spherical and non-spherical objects in ocean water, to characterize the effect of ensembles of micro-organisms and inorganic particulates on the propagation of polarized light through sea water, and to assess the importance of scattering to underwater imaging techniques and irradiance calculations.

SCIENTIFIC OBJECTIVES

The scientific objectives are to develop a numerical or analytical model that predicts angle-dependent scattering of polarized light from ensembles of non-spherical marine organisms, detritus, and inorganic particulates, and to verify and examine the validity and range of applications of the model by comparison with exact calculations and/or experimental results as appropriate. Specific tasks toward these objectives are:
   (1) to make experimental measurements, in the laboratory, of light scattering from samples of micro-organisms and inorganic particles in ocean water,
   (2) to develop an artificial neural network to recognize features in the Mueller matrix elements associated with the optical properties and irregular shape of ocean scatterers, and
   (3) to continue to refine and enhance the coupled-dipole approximation method.

APPROACH

Our past research efforts to understand and quantify light scattering in the ocean were focused on the experimental measurement of the Mueller scattering matrix or its calculation from optical properties of the scattering medium. Although experimental measurements and mathematical modeling continue to be important, much of the current work is concentrated on an inverse problem. That is, given the values of the Mueller matrix elements as a function of scattering angle, what are the relative index of refraction and effective size parameter of the particles that scatter the light? Furthermore, if the particles are non-spherical, is there a preferred orientation of these particles? The complexity and nature of this task suggests the use of an artificial neural network, a computer system comprised of a number of simple, interconnected processing elements, called neurons or nodes, operating in parallel.

1. REPORT DATE **30 SEP 1997**	2. REPORT TYPE	3. DATES COVERED **00-00-1997 to 00-00-1997**
4. TITLE AND SUBTITLE **Experimental Measurements of the Mueller Scattering Matrix for Marine Micro-organisms**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Tennessee State University,Department of Physics and Mathematics,3500 John Merritt Blvd,Nashville,TN,37209-1561**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT **Same as Report (SAR)**	18. NUMBER OF PAGES **6**	19a. NAME OF RESPONSIBLE PERSON
a REPORT **unclassified**	b ABSTRACT **unclassified**	c THIS PAGE **unclassified**			

The back-propagation neural network selected for the light scattering analysis takes a training example, an input and its corresponding output, and makes small modifications in the network weights and biases to minimize the difference between the current response of the network and the target response. The Mueller matrix elements S_{12} and S_{34} as functions of the scattering angle proved to be good predictors of both size parameter and index of refraction of the scattering sample. The coefficients of their Fourier series expansions were used as input to the neural network with size parameter and index of refraction as targets. Better results were obtained by training two separate networks, one for size parameter and one for relative index of refraction, than by training one network to predict both values. As an alternative to experimental data, the networks were trained with Mie calculations to represent scattering media containing spherical particles and coupled-dipole calculations to represent media containing irregularly-shaped particles. The two networks were trained with similar training sets but with different targets. The neural net that predicted size parameter was trained to be insensitive to variations in index of refraction, whereas the neural net that predicted index of refraction was trained to be insensitive to variations in size parameter.
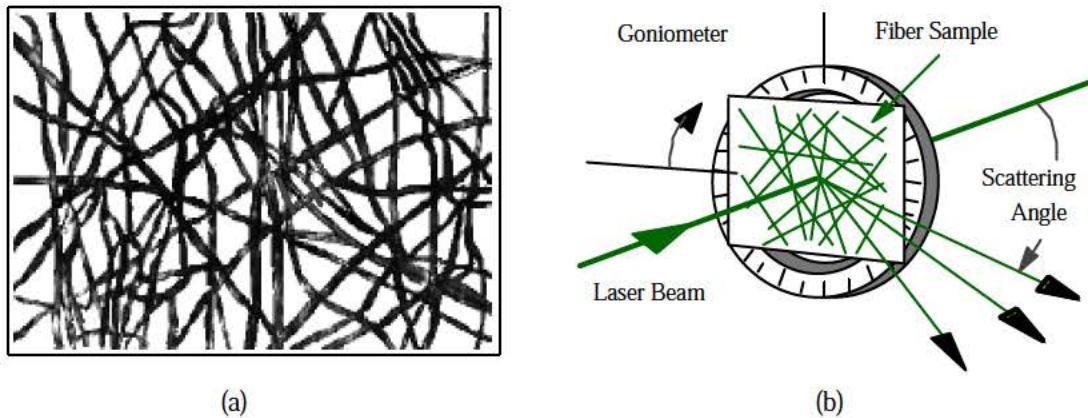

(a)   (b)

Figure 1. (a). Photograph of microscopic wood fibers taken with a phase contrast microscope at a magnification of 100x. Image enhancement computer software was used to remove blurred images of fibers not in focus due to limited depth-of-field of the microscope. (b) Sketch of the experimental set-up of sample positioned on the goniometer.

A more direct method was found to detect and measure a preferred orientation of the particles in a scattering sample, so it was not necessary to use neural network analysis in this case. Examination of both theoretical and experimental values of the matrix elements, S_{22} and S_{23} for collections of fibers or cylinders indicated that they were particularly sensitive to particle orientation. For a collection of cylinders oriented in a plane, S_{22} has a maximum value at scattering angles around 90° when the largest number of cylinders are oriented perpendicular to the scattering plane and the value decreases as the cylinders are rotated toward the horizontal. S_{23}, however, has its minimum values when cylinders are aligned either perpendicular or horizontal to the scattering plane, and it is mostly positive when the cylinders are tilted in one direction from the vertical and mostly negative when they are tilted in the other direction. Experimental measurements of S_{23} are small and usually very noisy, but when used in conjunction with S_{22}, these measurements can yield important orientation information. For the experimental arrangement,

both S_{22} and S_{23} showed the largest sensitivity to orientation of fibers for scattering angles from 50° to 90°. Measurements of these elements for a given sample orientation were averaged over this range of scattering angles and plotted as a function of sample orientation angle.

Microscopic fibers, often cellulose, were used for the experimental measurements since they can be modeled by homogeneous "infinite" cylinders extremely well. They have a small relative index of refraction and many have diameters that are comparable to numerous marine micro-organisms of interest. The exact solutions offered by the Rayleigh model and approximate solutions of the coupled-dipole model provide a basis of comparison with experimental measurements. In the experimental set-up, the fiber samples were confined to a plane perpendicular to the scattering plane and rotated about the vertical by an arbitrary angle (usually 45°) to the incident beam. The sample was the rotated about an axis perpendicular to the sample plane, producing different fiber orientations with respect to the scattering plane using a goniometer as shown in Fig. 1(b). In general, two angles are necessary to determine the orientation of a cylinder (or fiber) in three dimensions. If the fibers are confined to a plane, however, one of the two angles is constant and the mathematical modeling of the light scattering from the sample is considerably simplified.

WORK COMPLETED

The design and initial training of artificial neural networks that predict the size parameter or the relative index of refraction of a light scattering medium given its S_{12} and S_{34} matrix element was completed during the past reporting period. During the current reporting period, these neural networks were further trained by including experimental data and additional analytical calculations using the coupled-dipole approximation in the training sets.

Experimental measurements of complete sets of Mueller matrix elements were made for several samples and just the elements S_{22} and S_{23} were made for more than twenty samples. Sample types varied from silk fabric with cross threads removed (all fibers aligned in the same direction) to hand-made paper (fibers in completely random orientation.) Calculations of the matrix elements using the coupled-dipole method were made for the extreme cases, perfect alignment and random alignment of cylinders, as well as for a Gaussian distribution of cylinders for comparison with the experimental measurements.

The orientation of fibers in a sample was determined by taking photographs similar to that shown in Fig. 1(a) of a magnified image of the fibers using a phase contrast microscope. The photographs were scanned into a computer program that measured the orientation of each fiber with respect to the bottom edge of the photograph. Analysis of this image and a number of other images at nearby locations in the same sample yielded the number of fibers at a given orientation angle as a function of orientation angle. Some samples showed very nearly Gaussian distributions of the fibers about the vertical (right edge of the sample) while others showed little preferred orientation of the fibers.

RESULTS

In both experimental measurements and analytical models of collections of fibers in a plane, the normalized matrix element, S_{22} was averaged over a range of back-scattering angles, usually from 55° to 75°, for a given orientation of the sample. Averaging the measurements (or calculations) was important, but the exact range over which they were averaged did not appear to be critical. The sample was then rotated by a small angle and the light scattering measurements were repeated until the sample had been rotated 180°. The results of the coupled-dipole calculations for cylinders aligned in one direction are shown on the left graph and experimental measurements for silk fabric are shown on the right graph of Fig. 2. For the case of hand-made paper, the experimental measurement of the average S_{22} was nearly constant as the sample was rotated. In the couple-dipole calculation for the equivalent case (random orientation) it was also constant. Although different in magnitude, the coupled-dipole calculations agreed well in dominate features and symmetry with the experimental measurements. The graph peaks at 90° in both cases, the angle at which the cylinders or fibers were aligned perpendicular to the plane. Clearly, this approach offers potential for developing an instrument that can determine the orientation of a collection of cylindrically-shaped objects

The success of the simple neural networks described in this report and the excellent agreement between experimental measurements and the coupled-dipole approximation of polarized light scattering are important steps in our goal of predicting the optical properties, size parameter, shape, and orientation of the microscopic particles that make up a scattering medium.
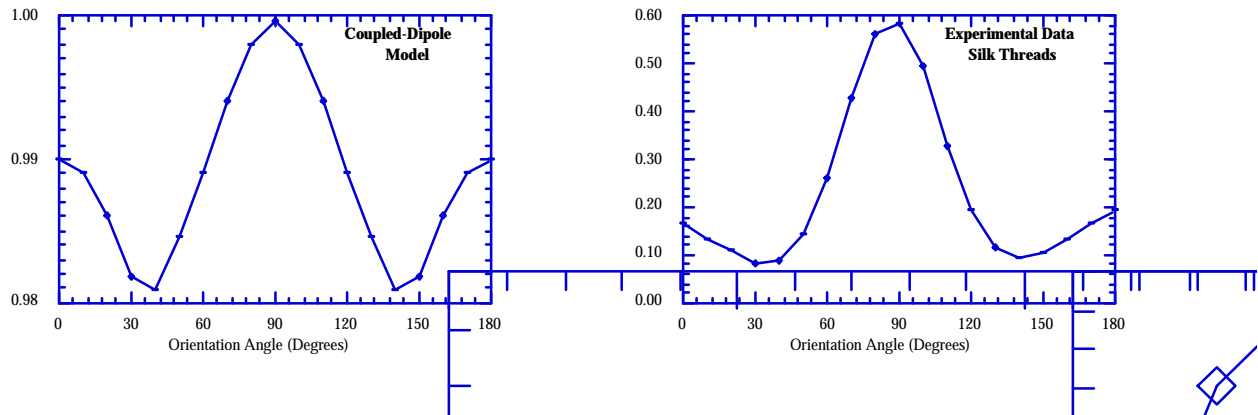

Figure 2. The normalized Mueller matrix element S22 averaged over scattering angles 55° to 75° and plotted as a function of the orientation of the sample. The cylinders in the coupled-dipole model and the silk threads in the experimental set-up are oriented vertical to the scattering plane at the orientation angle, 90°. (See Figure 1.)

IMPACT/APPLICATION

Currently, artificial neural networks are being applied to large classes of problems. Conventional computer techniques require detailed, explicit specification of the rules governing each application, must be virtually perfect in order to work, and require programming changes for every new or changed situation. This has, in the past, made computers of limited help in many challenging problems. Artificial neural networks do not require detailed, explicit specification of the rules governing each application, but rather they learn by example. They do not require

perfection in order to give a good solution, and require no programming changes for every new or changed situation. Furthermore, since neural networks can be hardwired, they can be easily incorporated into a light scattering instrument.

TRANSITIONS

The following projects make use of computer software and/or experimental methods developed in this research for measuring and modeling the light scattering by irregularly shaped particles:

1 - The coupled-dipole approximation in which the anisotropy of hemoglobin is described by ellipsoidal polarizability tensors at each dipole site is being used in a study of sickle cell hemoglobin at Wake Forest University. The study is funded by NIH.

2 - A version of the coupled-dipole approximation is being used in a project funded by DOE at Berkeley Lab for modeling soot particles in diesel exhaust. The goal of that project is to develop an instrument, possibly using our neural network, for measuring sizes of the soot particles.

3 - In another DOE funded project at Berkeley Lab, experimental methods developed by this project are being used to help design an instrument for on-line measurement of the alignment of the fibers in paper production.

RELATED PROJECTS

There are no current projects directly relation to the work reported here. However, this work was a component of past ONR-sponsored projects and is related to a current project proposed by Hunt and Quinby-Hunt at Berkeley Lab for the measurement of light scattering in both sea water and the sea-air boundary layer .

REFERENCES

D.Kim-Shapiro, and P.Hull. 1997. Polarized light scattering from sickle hemoglobin polymers, J. Chem. Phys. August, 1997.

E.Purcell, and C. Pennypacker. 1973. Scattering and Absorption of Light by Non spherical Dielectric Grains, Astrophy. J. Vol.186, 705.

M.Singham, S.Singham, and G.Salzman. 1986: The scattering matrix for randomly oriented particles, J. Chem. Phys. 85, 3807.

B.Bronk, W.Van De Merwe, and M.Stanley. 1992: In vivo Measurement of Average Bacterial Cell Size from a Polarized Light Scattering Function, Cytometry, Vol.13, 155.

J.Goodman, B.Draine, and P.Flatau.. 1991: Application of fast-Fourier transform techniques to the discrete-dipole approximation, Optics Letters, Vol.16, Optical Society of America.

P.Smith, D.Green, and R.Naimimohasses. 1994: Some Investigations on neural processing of scattered light in water quality assessment. <u>IEE Proc.-Vis. Image Signal Process.</u>, Vol. 141, No.4, 261.